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Brief Communication: Investigating the invisible subsurface stormflow process through a thorough and systematic study across sites and scales

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Abstract. Subsurface stormflow (SSF) is one of the least studied and therefore least understood runoff generation processes because detecting and quantifying SSF is extremely challenging. However, the impact of SSF on streamflow dynamics and water quality is much larger than commonly assumed. The hydrologic community should therefore not shy away from the challenge to monitor SSF, but should instead join forces, make creative use of novel sensing techniques and systematically tackle the investigation of this elusive process. While this endeavor is high in effort and risk, it also comes with the potential of high gain. We here describe the challenges and propose a possible way forward.

Short Summary

Subsurface stormflow (SSF) is one of the least studied and therefore least understood runoff generation processes because detecting and quantifying SSF is extremely challenging. We present an ongoing concerted experimental effort to systematically investigate SSF across four catchments using a variety of methods covering different spatial scales. Centerpiece of this effort is the construction of 12 large trenches to capture and monitor SSF.

Motivation

A recent meta-study on hydrological processes observed in 400 catchments around the globe found that subsurface stormflow was widely reported across almost all biomes (McMillan et al., 2025), which confirms the urgent need to develop a better

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understanding of this process. However, measuring subsurface runoff processes is challenging, as they cannot be observed directly. As a result, a wide variety of experimental approaches has been used at hydrological study sites worldwide, usually focusing more on proxies than direct measurements (see review by (Blume and van Meerveld, 2015). They range from measurements of matric potential at the plot (Kienzler and Naef, 2008) and hillslope scale (Anderson and Burt, 1978) to tracer approaches at the catchment scale (e.g., Gabrielli and McDonnell, 2020). Hydrogeophysical methods may have the potential to identify subsurface flow paths (e.g., Angermann et al., 2017). Most of these in-situ approaches have only been used on the hillslope scale without upscaling the information obtained to the catchment scale. Nevertheless, if we really want to understand this process and its impact on flood generation and water quality at the catchment or larger scale, we will at some point have to move beyond the scale of single, highly instrumented hillslopes. In general, the different experimental methods can be distinguished in hillslope- and stream-centered approaches (Blume and van Meerveld, 2015). However, Blume and van Meerveld (2015) also emphasize that it is necessary to combine these approaches to advance the process understanding of SSF generation, not only at single hillslopes but also at the catchment scale. Possible novel developments with respect to experimental methods could include the advancement of in situ sensors for water chemistry, providing high temporal resolution datasets and – if sensors are cheap enough – allowing for highly resolved spatial coverage. Another possibility could be the use of new tracers, such as diatoms (Pfister et al., 2017) and the local microbial community composition inferred via environmental DNA (e.g., Mächler et al., 2019) which are specific to a certain depth or habitat (for example, the upper soil horizons or weathering zone) or artificial tracers, such as DNA, which have the advantage of being infinite in number and can thus be applied to as many hillslopes as required (e.g., Foppen, 2023; Foppen et al., 2011)).

In hydrological models, SSF is mostly represented as the discharge of one or several reservoirs that initiate fast subsurface runoff (e.g. Seibert and Vis, 2012). In order to represent SSF correctly, model parameters that control the simulated SSF dynamics have to be estimated a priori (Steinbrich et al., 2016) or calibrated via inverse parameter estimation (Vrugt et al., 2008). Due to the limited available information, the distinction of SSF from other runoff processes such as surface runoff or groundwater flow is often difficult (Seibert and McDonnell, 2002). When models with SSF-related parameters are calibrated based on discharge records at the catchment outlet, the SSF simulations are highly uncertain and the simulated outputs can appear right for the wrong reasons, i.e., the high goodness-of-fit for total discharge can be the result of wrong simulations of surface runoff, SSF and groundwater flow. Previous modelling studies indicated the value of experimental information to improve model realism, for instance using hydrometric information (Hopp and McDonnell, 2009), hydrochemical information (Hartmann et al., 2017) or stable water isotopes (Schwerdtfeger et al., 2016; Sprenger et al., 2015). However, all of these studies were performed at one site using only one hydrological model. A general lack of understanding of SSF processes (Chifflard et al., 2019; McGuire et al., 2024) inhibits the development and testing of SSF routines in hydrological models at larger scales (Fan et al., 2019). Modeling SSF at the hillslope scale with physically-based models has been successful (e.g. Hopp et al., 2011; Hopp and McDonnell, 2009; Meerveld and Weiler, 2008), but extrapolation to a larger scale is problematic due to the spatial variability of SSF (and the fact that it frequently manifests itself as preferential flow), the threshold-driven nature of the process, the multitude of interacting controls and the lack of adequate data for parameterizing the models.

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To obtain a better handle on SSF a thorough and systematic investigation of SSF across sites and scales is imperative (Chifflard et al., 2019; McGuire et al., 2024). We identified four challenges that need to be addressed to make this more feasible.

Challenge 1: Development of novel experimental designs and methodologies from the hillslope to the regional scale

This challenge requires the development of a systematic experimental design for the investigation of SSF, as well as its controls, and the development of an experimental protocol (best practice) for SSF detection and measurement. The experimental design should combine multiple methods covering multiple scales at multiple sites and the assessment of measurement uncertainties, measurements that close the observation gaps between the hillslope and the catchment scale to provide insights on distributed hillslope-stream connectivity at the larger scale and the importance of the riparian zone as a potential gatekeeper of SSF contributions to streamflow, and finally the development of hydrograph-based signatures and proxies of SSF that enable assessment of SSF occurrence at the larger scale.

Challenge 2: Identification, characterization and prediction of the spatial patterns of SSF

This challenge applies to both experimental work and modelling. Experimentally, this involves systematic inter-site comparisons and includes assessments of how surface and subsurface characteristics (such as topography and soil depth) and structures (such as layer interfaces and preferential flow paths) affect SSF occurrence. This also includes assessing the impact of riparian zone characteristics on distributed hillslope-stream connectivity at the larger scale.

On the modeling side, it is necessary to benchmark the performance of different spatially distributed models in simulating spatial SSF patterns based on readily available information (such as streamflow observations or soil maps) and with the newly collected information on spatial patterns of SSF occurrence. Consequently, the model benchmarking will provide new insights on the limits of the parameterization of SSF processes based on common datasets and on the value of SSF-specific data collection to improve SSF simulations.

Challenge 3: Identification, characterization and prediction of thresholds and cascading effects of SSF

This challenge requires monitoring the dynamics of subsurface connectivity and threshold identification across scales, identifying where and when SSF generates saturation overland flow (return flow), generating frequency distributions of SSF occurrence across scales and benchmarking the performance of lumped and spatially distributed models in reproducing these thresholds, patterns and frequency distributions for SSF at the catchment scale, using readily available data and newly collected SSF data. For the latter, new methods to include the highly resolved experimental data obtained at different scales into model parameterization and calibration need to be developed.

https://doi.org/10.5194/egusphere-2025-4424
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Challenge 4: Impact of SSF on streamflow and water quality at the catchment and basin scale

A thorough testing of the effects of SSF on streamflow and water quality at the catchment and basin scale includes the assessment of the SSF effects on transit time distributions, young/old water fractions, velocity and celerity, and the export of solutes including nutrients, dissolved organic matter (DOM), and weathering products. An impact assessment across scales is needed to identify at what scale SSF is (most) relevant for floods, water storage and the export of matter. All of these assessments need to be based on experimental work and modeling (including model inter-comparison).

A concerted effort is needed

In an ongoing concerted effort carried out in a DFG Research Unit that focusses on SSF, we approach these challenges with an exceptional systematic experimental approach. The centerpiece of this effort is the installation of three large trenches (15 m long and 2-3 m deep, see Figure 1) in four different catchments (three low-mountain range catchments in Germany and one catchment in the Austrian Alps).

Figure 1: Construction of trenches in German low-mountain ranges.

These 12 trenches allow for the continuous monitoring of SSF at two different soil depths (an example of measured time series is shown in Figure 2). This data set on the occurrence of SSF, its threshold dynamics, depth distribution and amounts, serves as "ground truth" for other types of measurements as well as models. The trench observations are accompanied by numerous complementary measurements (Fig. 3). These complementary efforts include artificial rainfall experiments, geophysical exploration and geophysical time-lapse measurements, sequential stream gauging, detailed and distributed water chemistry monitoring (snapshot and event-based), stable isotopes and radon, and also the investigation of novel tracers such as natural and artificial environmental DNA (eDNA) and DOM composition, distributed monitoring of shallow groundwater fluctuations with extensive observation well networks and distributed fiber-optic temperature sensing. These measurements are more easily interpreted in light of the ground truth dataset for SSF and can thus be assessed for their potential as proxy measurements or indicators for SSF occurrence.

https://doi.org/10.5194/egusphere-2025-4424
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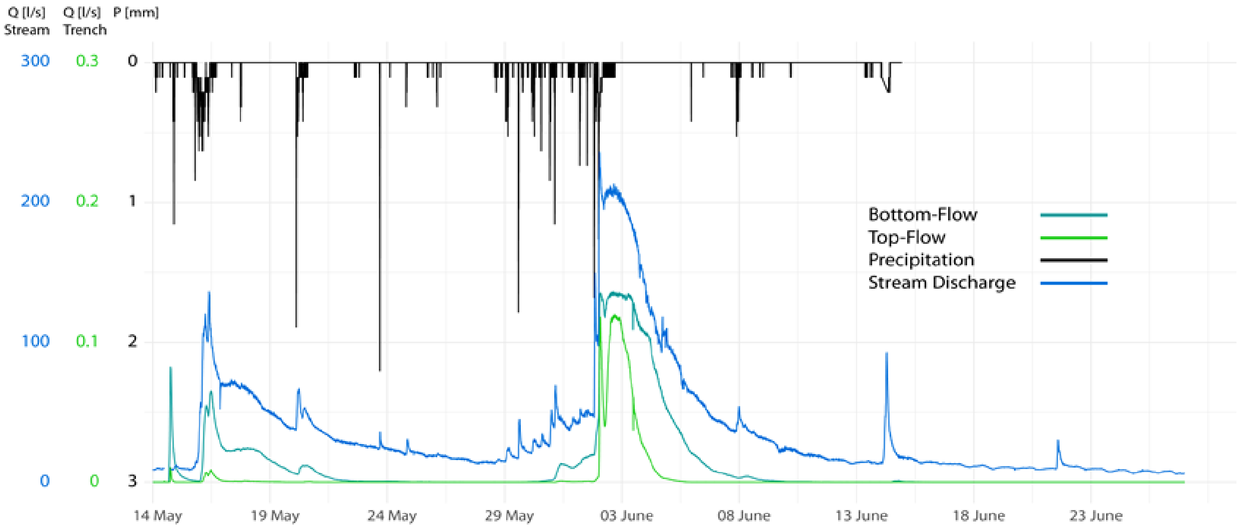

Figure 2: Exemplary time series of SSF event response.

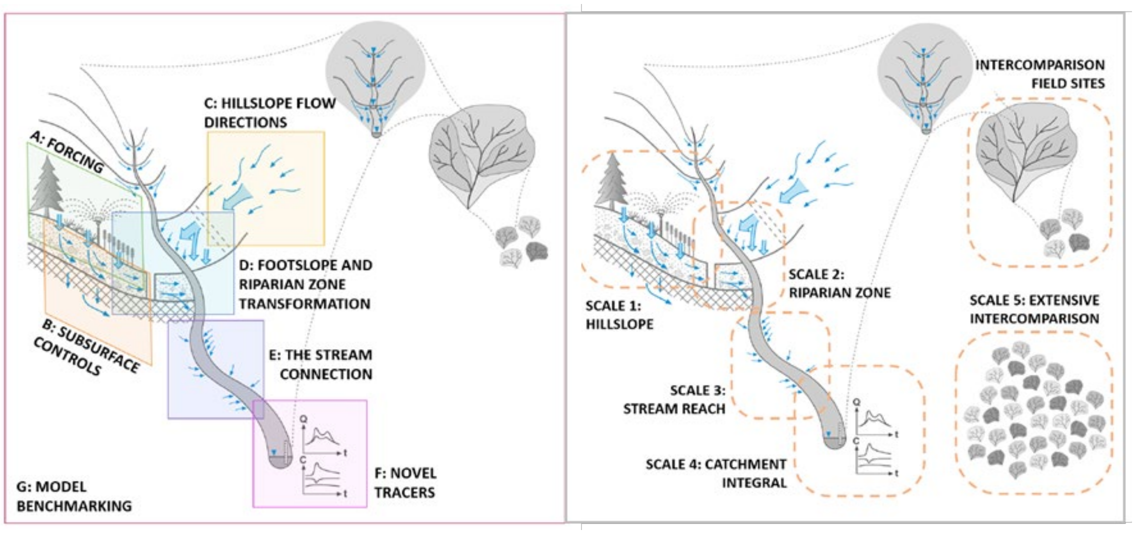

Figure 3: left: Different angles/aspects of SSF which need to be considered in order to understand SSF; right: Nested scales at which SSF needs to be studied and considered for its impact.

In their review paper on SSF McGuire et al. (2024) concluded: "Hydrologists have an excellent foundation to address the current gaps in understanding, simulation and generalisation of interflow across landscapes and scales. However, the community needs to overcome the often site-specific perspective on interflow processes and reverse the decline in the number of field studies in hydrology (Burt and McDonnell, 2015). …There is a clear community effort needed in re-vitalizing experimental hillslope studies especially with a view on synthesizing across sites, … with consistent and transferable experimental protocols." With the ongoing effort described above we attempt exactly that. However, our experimental investigations do not stop at the hillslopes equipped with the trenches, but cover various spatial scales as shown in Figure 3.

Systematic replication of the measurements in the three low-mountain range catchments and the alpine site provides an optimal basis for comparison of hillslope and catchment responses, to identify general patterns and responses and move beyond the uniqueness of place (Beven, 2020, 2000). The identification of adequate proxy measures will ultimately allow the assessment of SSF occurrence and SSF impacts at sites where trench data is not available. Therefore, even though this extensive experimental effort is a big investment in terms of time and equipment with the omnipresent risks of failure inherent in experimental work, it has the potential of significantly advancing our understanding of this process itself, but also such that future investigations elsewhere might be able to rely with more confidence on simpler indirect measurements of SSF.

Data availability

The data shown in the exemplary time series can be provided by the authors upon request.

Author contributions

TB prepared the manuscript, with feedback from all co-authors.

Conflict of interest

The authors declare no conflict of interest. However, MW is a member of the editorial board of HESS and TB is Chief Executive Editor.

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https://doi.org/10.5194/egusphere-2025-4424
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